North Pacific Acoustic Laboratory: Deep Water Acoustic Propagation in the Philippine Sea

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LONG-TERM GOALS

The North Pacific Acoustic Laboratory (NPAL) program is intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, (ii) the structure of the ambient noise field in deep water at low frequencies, and (iii) the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

OBJECTIVES

During 2009–2011 three experiments were conducted to study deep-water acoustic propagation and ambient noise in the oceanographically and geologically complex northern Philippine Sea: (i) 2009 NPAL Pilot Study/Engineering Test (PhilSea09), (ii) 2010–2011 NPAL Philippine Sea Experiment

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(PhilSea10), and (iii) Ocean Bottom Seismometer Augmentation of the 2010–2011 NPAL Philippine Sea Experiment (OBSAPS) (Worcester *et al*., 2013).

The goals of the Philippine Sea experiments included (i) understanding the impacts of fronts, eddies, and internal tides on acoustic propagation, (ii) determining whether acoustic methods, together with other measurements and ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improving our understanding of the physics of scattering by internal waves and spice (density-compensated temperature and salinity variations), (iv) characterizing the depth dependence and temporal variability of the ambient noise field, and (v) understanding the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals.

APPROACH

The three NPAL Philippine Sea experiments are described in detail in Worcester *et al*. (2013). A brief summary follows.

PhilSea09. A short-term Pilot Study/Engineering Test was conducted in the Philippine Sea during April-May 2009. A single acoustic path was instrumented with a Teledyne Webb Research (TWR) swept-frequency source (T1) and a prototype Distributed Vertical Line Array (DVLA) receiver (Worcester *et al*., 2009). The DVLA consisted of two 1000-m subarrays: an *axial subarray* spanning the sound-channel axis and a *deep subarray* spanning the surface conjugate depth. Both moorings remained in place for about one month, while coordinated, ship-based measurements were made. These included transmissions to the DVLA from sources suspended from shipboard and recording of the T1 and ship-suspended source transmissions by the towed Five Octave Research Array (FORA).

PhilSea10. The 2010–2011 NPAL Philippine Sea deep-water acoustic propagation experiment combined measurements of acoustic propagation and ambient noise with the use of an ocean acoustic tomography array to help characterize this oceanographically complex and highly dynamic region. A full water-column-spanning DVLA with a combined total of 150 Hydrophone Modules was deployed within an array of six broadband TWR acoustic transceivers (T1-T6) from April 2010 until March-April 2011 (Fig. 1). The DVLA recorded the transmissions from the six sources in order to study acoustic propagation and scattering. Each acoustic transceiver also recorded the transmissions from the other transceivers, forming a six-element ocean acoustic tomography array with a radius of approximately 330 km.

During May 2010 MP-200 Multiport and HX-554 sources suspended from shipboard at ship station SS-500 transmitted to the DVLA (Andrew *et al*., 2010). During July 2010 a J15-3 source suspended from shipboard transmitted to the DVLA for the 2010 Mobile Ops (MOPS10) experiment.

Four acoustic Seagliders were deployed during November 2010 in the vicinity of the PhilSea10 moored array (Howe *et al*., 2011; Van Uffelen *et al*., 2013). The gliders measured temperature and salinity in the upper 1000 m of the ocean between the moorings and recorded the transmissions from the moored acoustic sources.

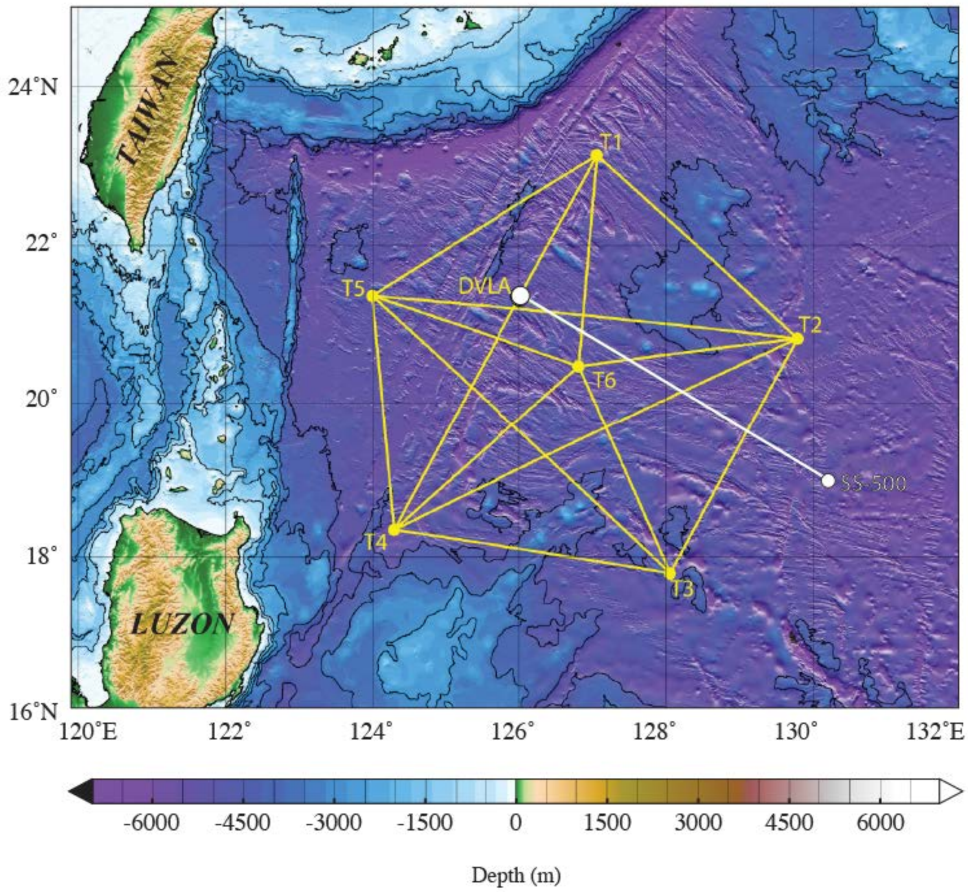

Figure 1. Geometry of the PhilSea10 experiment. A Distributed Vertical Line Array receiver was moored at DVLA. Broadband acoustic transceivers were moored at T1-T6. Ship-suspended sources transmitted to the DVLA from ship station SS-500. (Reproduced from Worcester et al., 2013.)

OBSAPS. A near-seafloor, 1000-m long O-DVLA (OBSAPS-DVLA) and an array of six ocean bottom seismometers (OBS) were deployed in the Philippine Sea during April-May 2011, immediately following recovery of the PhilSea10 moorings, to study the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals transmitted by a ship-suspended J15-3 source (Stephen *et al*., 2011).

WORK COMPLETED

Analysis. Time series of travel times have been produced for all acoustic transceiver pairs. The processing of the receptions to generate the time series employed estimator-correlator processing to account for the scattering of the acoustic signals by ocean internal waves and/or spice (Dzieciuch, 2014). The procedure consisted of pulse compression of the original receptions, beamforming of the data from the four-element hydrophone array at each transceiver (taking account of the noise levels on each hydrophone), and finally application of estimator-correlator processing. Viterbi tracking was then used to obtain time series of travel times for each ray path (Dzieciuch, 2014). The results for transmissions from T1 to T3 and the reciprocal path T3 to T1 are shown in Fig. 2. In this case the estimator-correlator processing used a coherent bandwidth of 15 Hz and correlation time of 30 s.

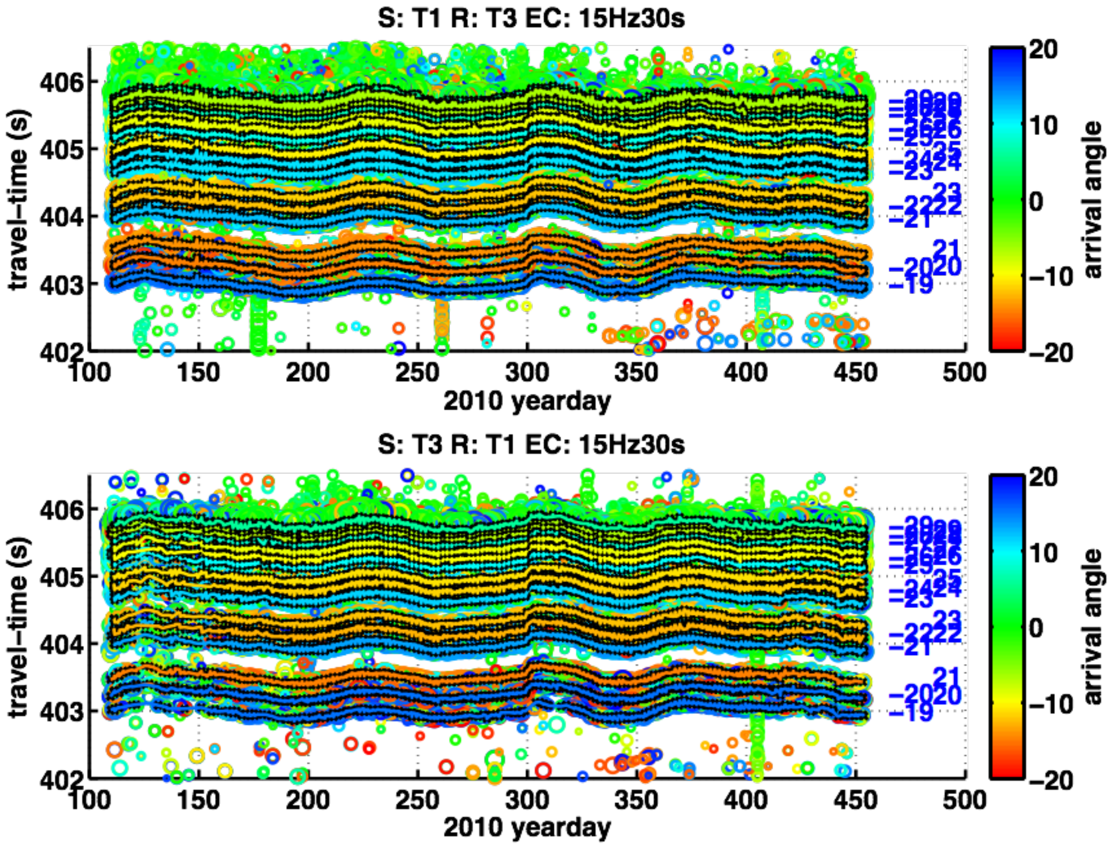

Figure 2. Time series of tracked ray paths for transmissions from T1 to T3 (top) and T3 to T1 (bottom) (filled circles with black borders). All arrival peaks over a threshold signal-to-noise ratio are also shown (open circles). The color indicates the vertical arrival angle.

The (non-uniformly spaced) time series of tracked travel times were analyzed to remove tidal signals and extract the low-frequency variability by performing a least square fit to a model consisting of long-period sinusoids (T = 500 days, 30 harmonics), 31 tidal harmonics, and broadened tidal lines at M2 and S1. The residuals then included the high-frequency, non-tidal variability. The resulting low-frequency travel-time series compare remarkably well with time series computed from an ocean state estimate made using a high-resolution regional implementation of the MITgcm that was constrained by satellite altimetric and Argo (but not acoustic) data (Fig. 3). Significant (~ 30 ms) differences remain, however.

The next step is to use the acoustic travel times to constrain the model by putting the acoustic paths in the cost function, generating gradients, and performing the assimilation. The required machinery is now in place. Initial efforts have used 10 rays for transmissions from T3 to T6 during the two-month period May-June 2010. A great deal of care is required to correctly derive the sound speed from the state estimate provided by the MITgcm and to properly compute the travel times. Preliminary results are encouraging, with significant reductions in the travel-time residuals after the travel times are used to constrain the model.

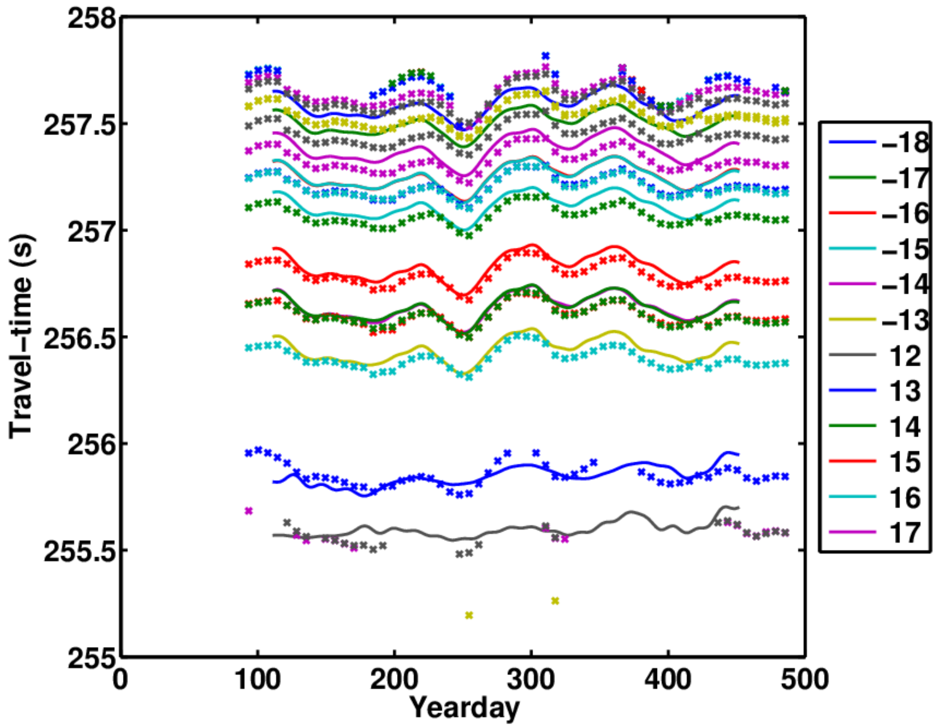

Figure 3. Measured low frequency travel time series (solid lines) for transmissions from T2 to T3 compared with travel times (×) computed from an ocean state estimate made using a high-resolution regional implementation of the MITgcm that was constrained by satellite altimetric and Argo data. The colors correspond to different ray identifiers.

D-STAR2 Development. During FY2014 we continued a design effort to develop a simpler, smaller, and cheaper DVLA controller employing the Microsemi (Symmetricom) Chip-scale Atomic Clock (CSAC). The CSAC eliminates the need for the complex dual-oscillator system currently employed in the D-STAR. The D-STAR2 is also designed to simplify the external connections needed by using the Precision Time Protocol (PTP) over Ethernet for time synchronization and Power over Ethernet to provide power.

RESULTS

Dzieciuch (2014) has developed improved signal processing for ocean acoustic tomography experiments to account for the scattering of the individual arrivals. The scattering reduces signal coherence over time, bandwidth, and space. The estimator-correlator is an effective procedure that improves the signal-to-noise ratio of travel-time estimates and also provides an estimate of signal coherence. The estimator-correlator smooths the arrival pulse at the expense of resolution.

After an arrival pulse has been measured, it must be associated with a model arrival, typically a ray arrival. For experiments with thousands of transmissions, this is a tedious task that is error-prone when done manually. Dzieciuch (2014) implemented the Viterbi algorithm to automatically perform peak tracking using an error metric that incorporates peak amplitude, travel time, and arrival angle. Repeatable, consistent results are produced that are superior to a manual tracking procedure. The tracking can be adjusted by tuning the error metric in logical, quantifiable manner.

These two developments together provide objective means of (i) smoothing the arrival signals to eliminate spurious peaks and (ii) tracking the resolved arrivals, replacing the various ad hoc procedures used to process data obtained from ocean acoustic tomography experiments in the past.

IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior.

RELATED PROJECTS

A large number of investigators have been involved in research related to the NPAL project during this period, including R. Andrew (APL-UW), A. Baggeroer (MIT), M. Brown (UMiami), R. Campbell (OASIS), T. Chandrayadula (NPS/IIT-Madras), J. Colosi (NPS), G. D'Spain (MPL-SIO), B. Dushaw (APL-UW), A. Ganse (APL-UW), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (Univ. Hawaii), J. Mercer (APL-UW), B. Powell (Univ. Hawaii), K Raghukumar (NPS), S. Ramp (SOS), R. Stephen (WHOI), I. Udovydchenkov (WHOI/Raytheon), L. Van Uffelen (SIO), K. Wage (George Mason Univ.), and A. White (APL-UW).

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